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Re-evaluating Copper Supply
The Crucial Role of Technology

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Abstract

Some authors argue that the energy transition is doomed to fail due to metal scarcity and the rising energy costs of extraction. They claim that as ore grades decline, mining will require more fossil fuel, leading to increased greenhouse gas emissions that could undermine decarbonization efforts. Additionally, they warn that expanding mining operations may result in higher freshwater consumption, waste production, and unacceptable environmental degradation.

A closer look at mineral exploration and mining suggests, however, that these concerns may be overstated. Advances in mining technology have enabled the efficient extraction of lower-grade deposits without major increases in energy use. As illustrated by the case of copper, mineral reserves and resources have constantly increased over time. While mining has environmental impacts, its contribution to land use, water consumption and loss of biodiversity remains relatively small. Metal costs have increased but remained broadly affordable.

The demand for metals will significantly increase as the energy transition combines with the digitalisation of the economy and an ever-increasing energy demand from developing countries. In the case of copper, the expected growth rate does not sensibly depart from the last decades. Reserves and resources are large enough to sustain that growth with only a small reduction in ore grade and could further increase if prices increase. A breadth of technical innovations will likely ensure that the specific energy consumption of copper mining does not increase, while the ongoing electrification of mines and decarbonization of electricity generation will ensure a continuous decrease in specific greenhouse gas emissions.

The real risks for the energy transition are the insufficient rate of increase in metal mining, including copper, and the geopolitical risks associated with high levels of concentration of mining activities and moreover in refining for a series of critical materials.

Résumé

Certains auteurs affirment que la transition énergétique est vouée à l'échec en raison de la rareté des métaux et de l'augmentation des coûts énergétiques de l'extraction. À mesure que les teneurs en minerai diminuent, l'exploitation minière nécessiterait davantage de combustibles fossiles, ce qui entraînerait une augmentation des émissions de gaz à effet de serre susceptible de compromettre les efforts de décarbonisation. En outre, ils avertissent que l'expansion des opérations minières peut entraîner une consommation accrue d'eau douce, une production de déchets plus élevée et une dégradation inacceptable de l'environnement.

Un examen plus approfondi de l'exploration et de l'exploitation minières suggère toutefois que ces préoccupations sont sans doute exagérées. Les progrès de la technologie minière ont permis l'extraction efficace de gisements à faible teneur sans augmentation majeure de la consommation d'énergie. Comme l'illustre le cas du cuivre, les réserves et les ressources minérales n'ont cessé d'augmenter au fil du temps. Si l'exploitation minière a des incidences sur l'environnement, sa contribution à l'utilisation des sols, à la consommation d'eau et à la perte de biodiversité reste relativement faible. Les coûts des métaux ont augmenté mais sont restés largement abordables.

La demande de métaux augmentera de manière significative car la transition énergétique se combine à la numérisation de l'économie et à une demande d'énergie toujours plus importante de la part des pays en voie de développement. Dans le cas du cuivre, le taux de croissance attendu ne s'écarte pas sensiblement de celui des dernières décennies. Les réserves et les ressources sont suffisamment importantes pour soutenir cette croissance avec seulement une petite réduction de la teneur en minerai, et pourraient encore croître si les prix augmentent. Un large éventail d'innovations techniques garantira probablement que la consommation d'énergie de l'extraction d'une tonne de cuivre n'augmente pas, tandis que l'électrification en cours des mines et la décarbonation de la production d'électricité garantiront une diminution continue des émissions de gaz à effet de serre associées.

Les véritables risques pour la transition énergétique sont l'insuffisante vitesse d'augmentation de l'extraction des métaux, y compris le cuivre, et les risques géopolitiques associés à des niveaux élevés de concentration dans l'extraction et, surtout, le raffinage pour une série de matériaux critiques.

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Introduction

The continuous rise in metal demand, particularly since the Second World War, has fueled rapid economic growth. This growth has been accompanied by a significant increase in population and a considerable improvement in the standard of living for billions of people. Global population growth is now entering a phase of slowdown and, in the coming decades, could reverse. Beyond a certain level of economic development, the demand for heavy industry gives way to the demand for services, which, while not entirely dematerialized, are nonetheless less material-intensive.

The energy transition aims to replace fossil fuels—gas, oil, and coal—with low-carbon generation sources, predominantly wind and solar, not just for electricity generation but also in buildings, industry, and transportation. This shift will significantly increase demand for metals essential for power production, distribution, and storage, particularly in electric vehicles. These include metals such as nickel, cobalt and lithium, as well as the famous –or infamous– rare earth elements. It also encompasses industrial metals like iron and aluminium, with a particular emphasis on copper, the central focus of this paper.

Simultaneously, the rapid growth of digitization, AI, data centers, and cryptocurrencies continues to drive metal demand. Governments in industrialized countries are increasingly concerned about dependence on foreign sources, particularly China, which has established a dominant position in metal extraction and especially refining.

In the long term, metal demand will stabilize and then decline as recycling meets an increasing share of this demand, although limited by the most dispersive uses, and by physical and economic constraints. However, in the coming decades, the urgent need to transition from a world primarily powered by fossil fuels to one powered mainly by low-carbon energy sources such as solar, wind and hydroelectric power, through expanded electric grids and the electrification of many applications, will sustain high metal demand. Can the mining industry meet this challenge?

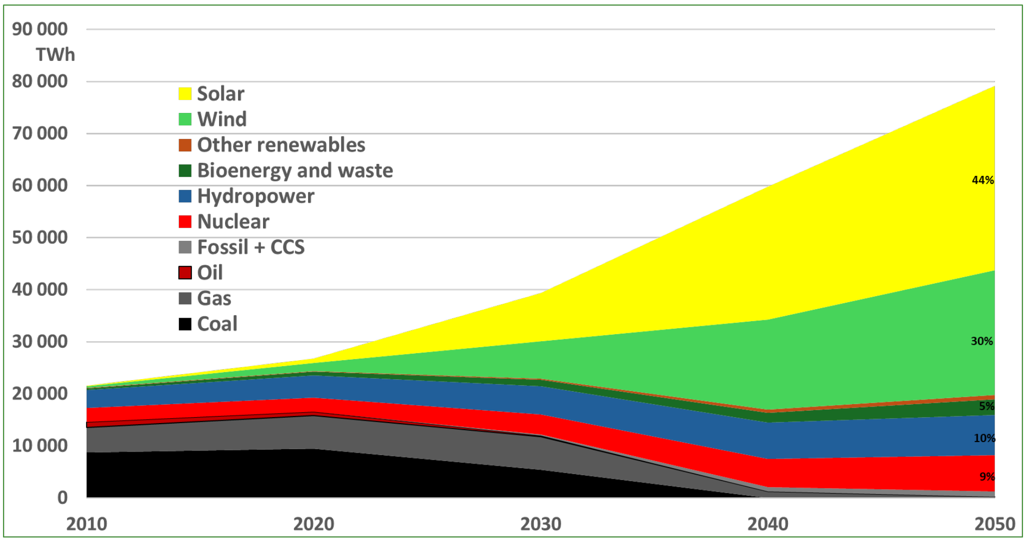
In its most recent report, the Intergovernmental Panel on Climate Change (IPCC) identified emission reduction options costing less than 20 dollars per ton of CO_2 equivalent, which account for more than half of the total emission reduction potential needed to stay on a 1.5°C pathway by 2030. The top two options are solar and wind energy, offering potentials of 3.3 Gt CO_2-eq/year and 3.08 Gt CO_2-eq/year, respectively. As a third option, the IPCC mentions reducing deforestation and the conversion of other ecosystems (2.28 Gt). Other energy sector options are mentioned, but with lower potentials and almost always higher costs: reducing methane leaks, bioenergy, geothermal and hydroelectric power, nuclear energy, and carbon capture and storage. (IPCC 2023)

Wind and solar energy technologies are primarily suitable for producing electricity rather than heat or fuel for transport. To reduce the use of fossil fuels —not only in electricity production, which represents only about 20% of final energy demand—, it will be necessary to electrify as much as possible the end-use energy sectors, including buildings, industries, and transportation.

Developing renewable energy sources, especially wind and solar, and electrifying energy uses are thus the most important means of reducing greenhouse gas (GHG) emissions. These strategies were highlighted in the strategic plans of several countries, including China, the United States of America (USA) (before Donald Trump's second administration), the European Union (EU), and others. They also figure prominently in the "Net Zero Emissions by 2050" (NZE-2050) scenario of the International Energy Agency (IEA), first published in 2021.

Figure 1 illustrates the rapid growth of wind and solar energy, as well as electricity consumption, in a recently revised scenario (IEA 2024). By 2050, electricity is expected to account for half of final energy consumption and two-thirds of "useful" energy, a term that accounts for the substantial losses incurred when burning fuels to produce electricity or mechanical power. Solar energy is projected to provide 44% of future electricity demand (photovoltaic solar at 42% and concentrated solar power at 2%), with wind contributing 30%, hydropower 10%, nuclear 9%, bioelectricity 4%, and both geothermal and coal with CO_2 capture at 1%.

Figure 1: Electricity production in the IEA's "Net Zero" scenario



Source: "Data from World Energy Outlook 2024", International Energy Agency (IEA), 2024.

Other institutions have published comparable scenarios. For example, Bloomberg New Energy Finance's NZE-2050 scenario envisions renewable sources providing 81% of electricity, with 9% coming from gas and coal with CO_2 capture.

Critical metals

Politicians, journalists and the general public became aware of the notion of "critical" metals or minerals when China imposed export restrictions on the country's rare earth elements (REE) in 2010. This caused global alarm, a hike in the price of REE and, more significantly, it alerted industrial countries to potential threats to the supply of certain metals that were essential for high-technology applications. Earlier, in the 1980s, the U.S. Department of the Interior and U.S. Geological Survey (USGS) had compiled a list of "strategic and critical materials" focused on military and industrial needs. The Chinese export restrictions then led to the compilation of lists of critical metals or minerals, the first in the USA in 2017, followed by separate lists from the EU, Japan and other countries. In these lists, a metal or mineral (both figure in most compilations) is defined as critical if there is a significant supply risk and if it has economic and strategic importance, particularly in relation to the energy transition. On this basis, the following metals are listed as highly critical in most lists: REE, lithium, cobalt, nickel, gallium, germanium, titanium, to which can be added the mineral graphite. Even though copper has considerable economic and strategic importance, it is generally not considered critical because the sources are widely dispersed in countries that have a reputation for being reliable suppliers. However, both the EU and the US have recently recognized the strategic value of copper, in EU's case by including it as a strategic raw material in its CRM list, while Trump's Executive Order from March 2025 enables the facilitation of permitting and financing for copper projects (without extending the CRM list to copper nevertheless).

In almost all lists, the REE are ranked as highly critical. This arises from China's stranglehold on the processing and refining of these metals –the country currently controls 60% of primary production and 85-90% of global refining. When the country imposed export restrictions in 2010, it was the source of a similar proportion of mined REE, but in the following years, the USA, Australia, Myanmar and other countries have developed mines that supply about 30% of global needs. The REE are not that scarce in the Earth's crust and grades in ore deposits are like those of copper. In addition, numerous REE prospects are known on all continents.

Despite this, the media and politicians in all countries seem mesmerized by the REE. These metals were highlighted in Trump's attempts to purchase Greenland and to obtain compensation for the US support of Ukraine. The president said he wants from Ukraine "500 billion dollars of *raw earth* [sic]....". His use of "earth" as a noun and in the singular suggests that the president imagines that a rare and exceptional type of soil underlies Ukraine's wheatfields. In fact, there is little evidence for large and viable REE deposits in the country. Some traces of REE mineralization are mentioned in Soviet-era reports, but none of these is currently mined. To put the figure of $500 bn in perspective, Bayan Obo in China, by far the world's biggest REE deposit, has REE resources worth only about $300 bn. Despite this, the media persistently refer to Trump's offer to Ukraine as the "rare earth" deal.

In economic terms, the REE are relatively unimportant commodities; the value of global REE production is only about 10% that of copper and comparable to that of base metals like zinc or lead. Their current prominence stems mainly from China's dominance in REE production and processing —and its readiness to leverage this control in response to U.S. trade pressure.

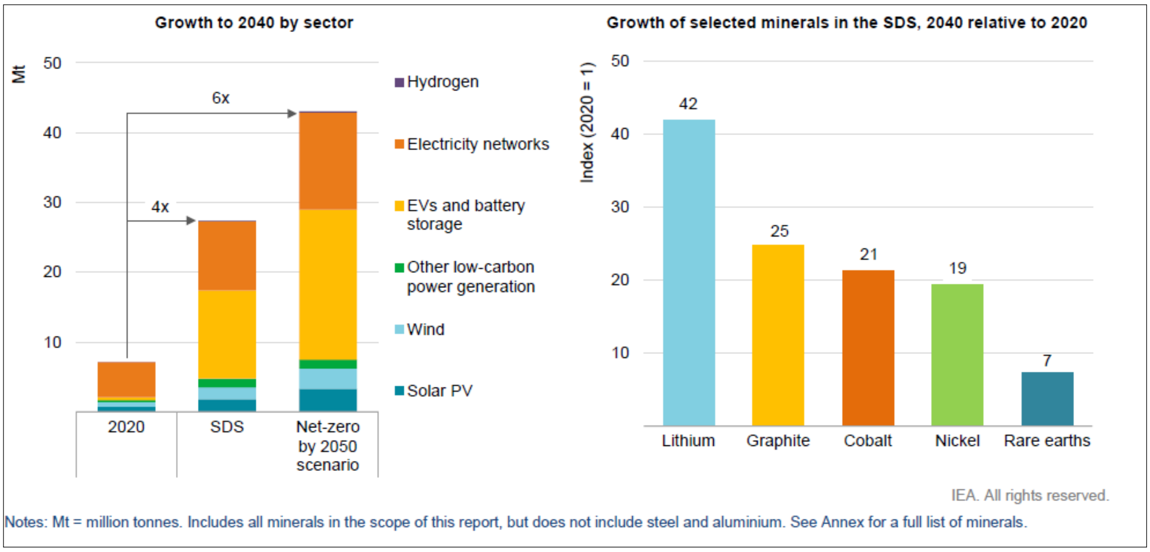
Copper matters

Even more than lithium or rare earths, copper—an excellent conductor of heat and electricity, ductile and easy to work with, and resistant to corrosion—is at the heart of the energy transition. Wind turbines, photovoltaic panels, electric vehicles, heat pumps, and power grids, notably offshore, all key components of the transition, make extensive use of copper.

Annual consumption is around 27 million tons (Mt) of copper, two-thirds of which are used in its pure form, primarily in electrical wires, cables, and plumbing. About 20% is used as brass (an alloy of copper and zinc), mainly in faucets, musical instruments, and mechanical parts. Approximately 5% is used as bronze (an alloy of copper and tin), for bells, statues, and some mechanical components like bearings. Other alloys together account for less than 5% of total production.

In 2021, the IEA stated that the demand for critical minerals in the transition technology sectors could increase sixfold by 2040, according to the first edition of the NZE-2050 scenario (figure 2). Nearly half of this increase would be needed to produce electric vehicles and storage batteries, one-third for power grids, and one-fifth for low-carbon electricity generation, mainly wind and solar power.

Figure 2: Mineral demand for clean energy technologies by scenario

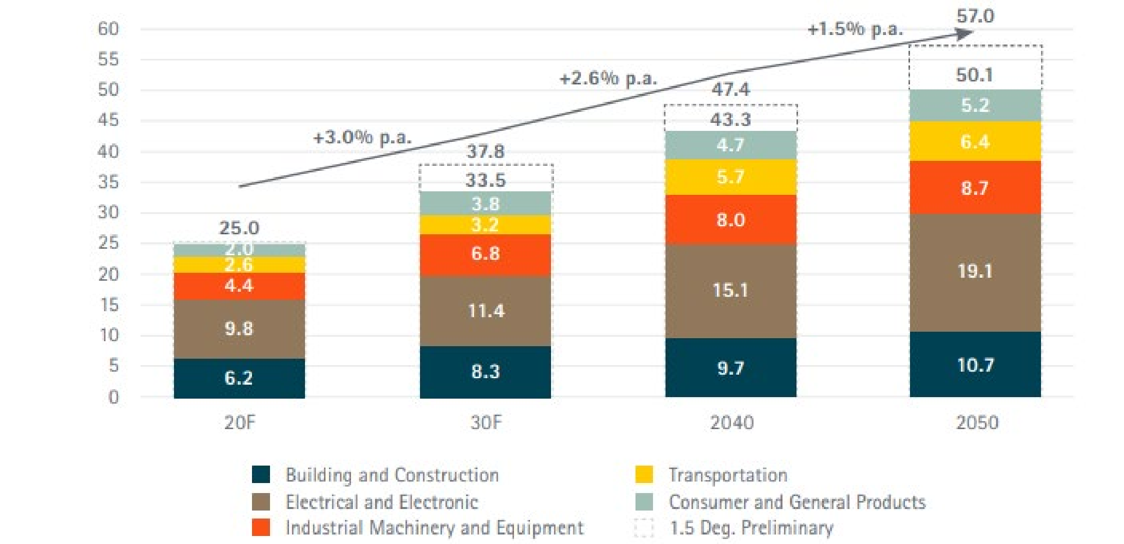


Source: "The Role of Critical Minerals in Clean Energy Transitions", IEA, 2021.

Consumption in these sectors is projected to increase by at least seven times for rare earth elements, about twenty times for nickel, cobalt, and graphite, and up to forty times for lithium. Although copper is usually not considered a critical mineral, its supply in the coming decades is uncertain in a world rushing into broad electrification. According to some analysts (e.g., Hache et al., 2020), humanity could by 2050 consume up to 89% of known copper resources or 54% of total estimated copper resources.

The actual demand will depend on the rate of economic growth, the fate of the energy transitions, the speed and depth of the electrification of current fossil fuel usages, and the growth of supply, which depends on the rate at which new resources are discovered. Most analyses converge toward a doubling of the annual copper consumption by 2050, as shown by the International Copper Association in figure 3. The actual copper demand also depends on substitution possibilities, influenced by relative price changes. Aluminum can substitute for copper cooling and refrigeration tubes, electrical equipment, and power cables. Optical fiber can replace copper in telecommunications, while plastics can be used instead of copper in drainpipes, plumbing fixtures, and water pipes. Titanium and steel are also alternatives in heat exchangers. Schneider Electric's Sustainability Research Institute concludes that the buildings sector presents the most promising opportunities for demand reduction. A 20% reduction in copper use in buildings could decrease total annual global copper demand by 5.4% by 2050 (T.A. Kwan, 2025).

Figure 3: The expected rise in annual refined copper demand between 2020 and 2050



Source: "Copper, the pathway to Net Zero", International Copper Association 2023.

For most uses in an increasingly electrified world, aluminum is the primary substitute for copper. Aluminum is a less efficient conductor –its conductivity per meter is only 61% that of copper– but it is three times lighter. For equal conductivity, an aluminum cable must have a section 1.5 to 2 times larger than a copper cable, but it will weigh less. Aluminum is already used routinely for overhead high-voltage aerial lines and large-section cables, but this substitutability has limits, particularly for applications requiring compact sections.

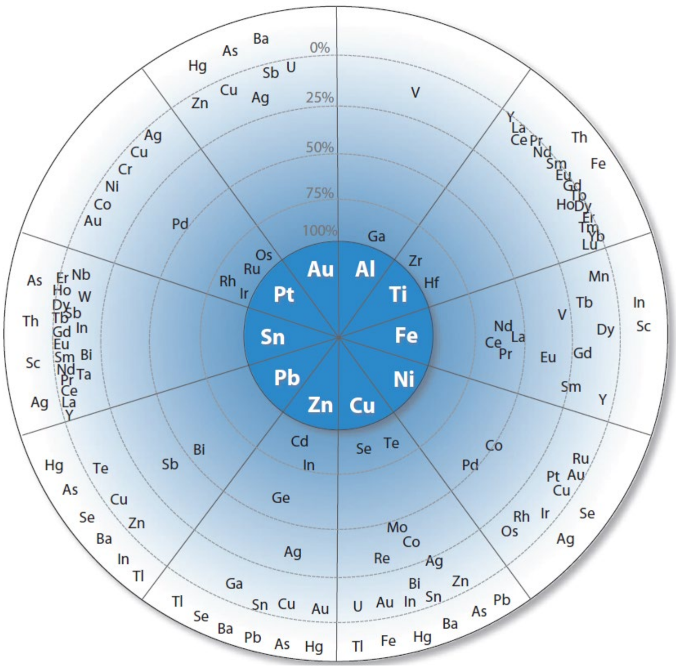
Of these 27 Mt of copper consumed in 2023, a third came from "secondary production", i.e. recycling. Copper can be recycled repeatedly without loss of performance, and there is no difference in the quality of primary and secondary production. Some novel substitution possibilities may generate significant amounts of copper to recycle, but the rapid increase in overall demand suggests the share of secondary production will not increase before the demand stagnates as most of the energy transition is realized, ideally in the second half of the century. Yet copper recycling will increase, not least as ageing power lines, plumbing and telecom cables are being replaced.

Co-recovered metals

Many metals are found as co-products or by-products of so-called "host metals", a phenomenon some authors refer to as "companionality". This has one good aspect: the energy and water demands, and environmental impacts can be lower. The reverse side of the issue is that the availability of co-recovered metals depends on mining the host metals.

Co-products are represented in figure 4 in the outer circle, with distances proportional to the percentage of their primary production derived from the indicated host metal. As shown, copper (Cu) mines globally produce most of the world's selenium (Se) and tellurium (Te), along with significant fractions of molybdenum (Mo), cobalt (Co), rhenium (Re), silver (Ag), gold (Au), and other metals. While silver has deposits rich enough for direct mining, 71% of total silver production comes from zinc, lead, copper or gold mines. Cobalt is a notable example: there is only one true cobalt mine in the world, located in Morocco. Elsewhere, cobalt is a by-product of copper and nickel mining.

Figure 4: The wheel of metal companionality



Source: N. Nassar, T.E. Graedel and E.M. Harper, 2015.

This paper focuses on copper—the first metal worked by humans, together with gold, the most widely used in the energy transition, and the one whose supply raises the greatest concerns in serious political and economic circles. It aims to discuss how technology changes in mining operations can impact future production and reserve levels, and thus change the perspective on this important metal.

The formation and exploitation of copper deposits

This section briefly discusses how a copper deposit is formed, how it is mined, and how the metals are recovered from the ore.

The formation of mineral deposits

An ore deposit is a portion of the Earth's crust where metals or materials vital to society are concentrated at levels significantly higher than normal. These concentrations result when natural geological processes, such as magmatism, sedimentation, weathering, or the circulation of hydrous fluids, are either disrupted or intensified to create economically mineable accumulations of valuable minerals.

Ore grades—the concentration of useful minerals or metals—vary significantly. For metals abundant in the Earth's crust, like iron or aluminum, typical ore grades range from 20% to 60%. In contrast, metals used in industry, like copper, nickel, or zinc, are found at percentage levels only, while precious metals such as gold or platinum are present at parts-per-million levels. There is a direct relationship between ore grade and price: iron sells for about US$ 200-400 per tonne, copper for approximately US$ 9 per kilo, and gold for around US$ 90 per gram.

Types and distribution of copper deposits

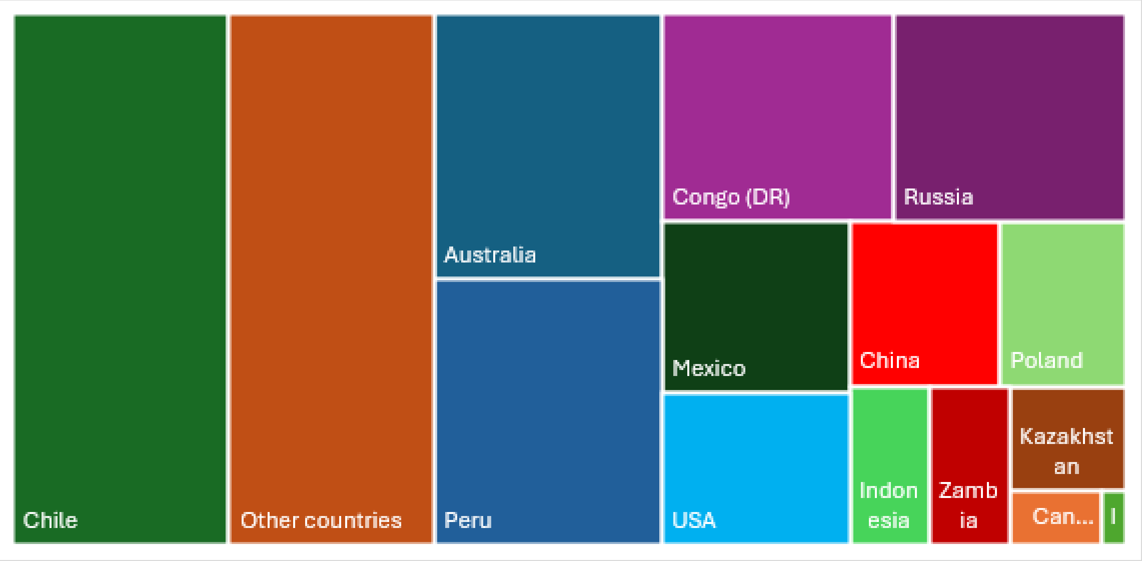
Here we provide only a brief description of the main types of copper deposits. For more details, the reader is referred to the Commodity Profile of the British Geological Survey or standard economic geology texts (e.g., L. Robb, 2004).

Unlike some other commodities where a few major deposits dominate the global market, copper deposits are found throughout the world. Almost every country contains some deposits and, except where political or societal pressures have prevented mining, these deposits are exploited. It is mainly for this reason that copper is absent from most lists of critical metals.

Nonetheless, the most important sources of copper are restricted to two main regions, each with a distinctive type of deposit. Most important are porphyry deposits, which occur in orogenic regions where a tectonic plate plunges beneath oceanic or continental crust. This is the setting of the major sources of copper, along the western margins of South and North America, on Pacific islands like the Philippines or Papua New Guinea, and in parts of eastern Europe and central Asia.

Figure 5 shows the distribution by country and illustrates the major importance of Chile.

Figure 5: Distribution by country of the world's copper reserves



Source: "Mineral Commodities Summary 2025", USGS, 2025.

A porphyry copper deposit is a large, low- to medium-grade ore deposit formed from hydrothermal fluids associated with granitic intrusions. The ore minerals, typically copper sulfides such as chalcopyrite and bornite, are disseminated through granitic plutons and within surrounding altered wall rocks. These alteration zones are dispersed about the central plutons and are composed of hydrothermal minerals such as clays and other phyllosilicates, quartz and K-feldspar. These deposits are thought to form when felsic magma intrudes the upper crust and releases hydrothermal fluids as pressure drops and the magma solidifies. These fluids carry the ore metals and, as they circulate through fractures and faults, they deposit the sulfides of copper and other metals.

The other major source is the African copper belt, which extends from the Democratic Republic of Congo to central Zambia. These deposits, which are described as "sediment-hosted" or "stratiform", consist of Cu-Fe sulfides disseminated within sandstones, shales and limestones. The ore also contains significant cobalt content and is the world's major source of this metal. The copper often exists as oxides such as malachite and azurite in weathered zones near the surface and sulfides deeper in the deposit (e.g., chalcopyrite, bornite). They are thought to form when oxidized copper-bearing solutions migrate through the sediment layers and precipitate when conditions change (e.g., a drop in pH or the presence of sulfides).

Mining and mineral processing

Whether an ore deposit can be mined depends on numerous factors, including its location, the depth and geometry of the ore body, the type of ore, local mining costs, and political or social issues. However, the most critical factors are the ore grade and the metal price. As metal prices rise, deposits with lower ore grades become economically viable for mining. This price dependence will significantly influence the future supply of metals as rich, easily accessible ore deposits become increasingly scarce.

Over the past few decades, mineral exploration has likely identified most near-surface ore deposits, especially in regions like Australia, Canada, Chile, Scandinavia, and the USA, where modern exploration technologies are widely used. Future exploration efforts will therefore focus on discovering deposits in underexplored regions, such as large parts of Africa and Asia, and many parts of Europe, where modern methods have yet to be applied.

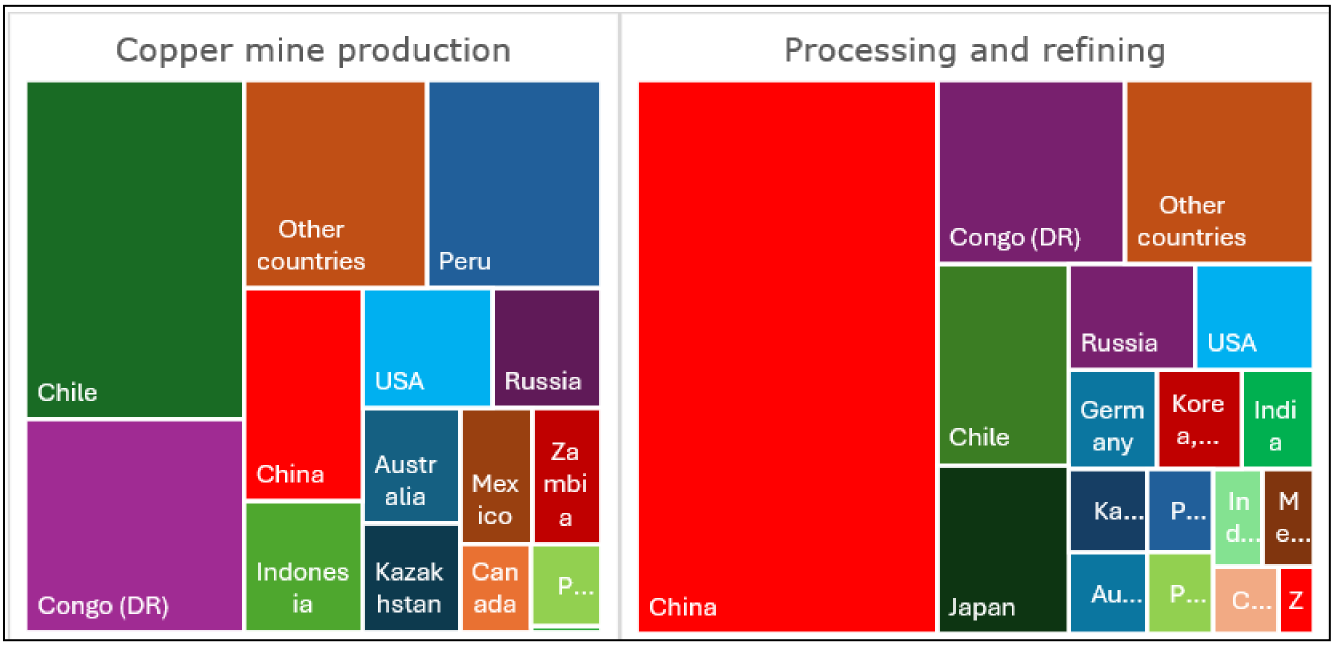
Particularly over the past few decades, mining of copper has been conducted mainly in large open-pit mines. Examples include some of the biggest mines in the world, such as Bingham Canyon in the USA and Chiquicamata in Chile, which both exploit porphyry copper deposits. Other, deeper-seated porphyry deposits are exploited in underground operations using innovative block-caving methods, notable examples being Grasberg in Indonesia and Cadia in Australia. In some cases, Grasberg and Chiquicamata, mining started in an open pit and then progressed to underground to exploit ore located well below the surface.

Sulfide ores are first crushed and ground to fine particles before undergoing flotation, which separates copper-bearing minerals from waste rock, producing a concentrate with 20% to 30% copper—significantly higher than the original ore, which typically contains between 0.3% and 1.7% copper (with an average of 0.58%). The concentrate is dried to reduce its water content and transported to smelters to remove the sulphur, then to refineries, where it undergoes pyrometallurgical treatment to remove impurities, followed by electrolysis to produce pure copper suitable for industrial use. A significant portion of the concentrates is shipped overseas, primarily to China, which imports around half of the world's copper concentrate shipments.

Oxide ores are processed using hydrometallurgy, which involves leaching with sulfuric acid to dissolve the copper, followed by solvent extraction to purify and concentrate the solution, and finally electrowinning to produce high-purity copper. This process is typically carried out near mine sites, though in some cases, intermediate products such as precipitates or copper at approximately 85% purity are also shipped.

Eleven nations extract three-quarters of the world's copper, but mineral processing and refining are more concentrated than mining and focused in different countries (figure 6).

Figure 6: Distribution of copper mine production (left) and refinery production (right) by country



Source: "Mineral Commodities Summary 2025", USGS, 2025.

Poland's copper giant KGHM – a strategic asset in Europe

Near Lubin, in the middle of Poland's ultra-dynamic and wealthy Lower Silesian Voivodeship, lies one of the world's largest copper deposits, exploited by KGHM Polska Miedź S.A. (further "KGHM"). Copper production is the world's eighth largest, as KGHM operates an underground mining area with three districts (Rudna, Lubin and Polkowice-Sieroszowice) almost twice as large as Paris. But the site also includes a concentrator plant and smelters as part of an integrated complex that employs almost 19,000 workers. Copper grade in ore is about 1.5% on average, mining operations lie up to 1,348 meters below with over 30 million tonnes of ore extracted, resulting in ca. 400,000 tonnes per year of copper in concentrate. When adding scrap and other concentrates, the complex produces ca. 590,000 tonnes of copper cathodes per year with about 99.99% purity. High-quality products are confirmed by the certificates issued by the London Metal Exchange, Futures Contracts Exchange in Shanghai and Shanghai International Energy Exchange (INE), and guaranteed by the following brands: HML for "Legnica" Smelter, HMG-S for "Głogów I" Smelter and HMG-B for "Głogów II" Smelter, under which they are registered on the London Metal Exchange as grade "A". About half of the cathodes produced are further processed by KGHM into copper wire rod, oxygen-free copper wire (also silver bearing) and granules. Poland is not only blessed with very large copper reserves: the mining production comes with byproducts such as metallic silver (making KGHM a global leader), and to a lesser extent, gold, rhenium, lead, sulfuric acid, selenium, copper sulphate and nickel sulphate.

The complex consumes about 2% of electricity demand and about 1% of Poland's gas consumption, and electricity costs have been rising faster than global copper prices. Improving productivity, reducing energy consumption, and ESG footprint are a priority, alongside safety, inside the complex, but also around the large tailings.

Last but not least, the GHG footprint of operations is expected to be reduced across time as Poland's electricity mix gradually decarbonizes (coal is being progressively replaced with wind, solar and later also nuclear, alongside gas as backup), and transporting the semi-finished or finished products will be progressively improved through the decarbonization of the truck fleet and maritime transport.

There is potential to sustain production for decades at such high levels and to progressively replace natural gas in the smelters with some lower methane footprint products. Production costs will be key, in a highly taxed environment, so unleashing major projects, including into deeper layers with higher production costs (notably for cooling and ventilation), will obviously require a long-term investment plan involving close coordination with the government.

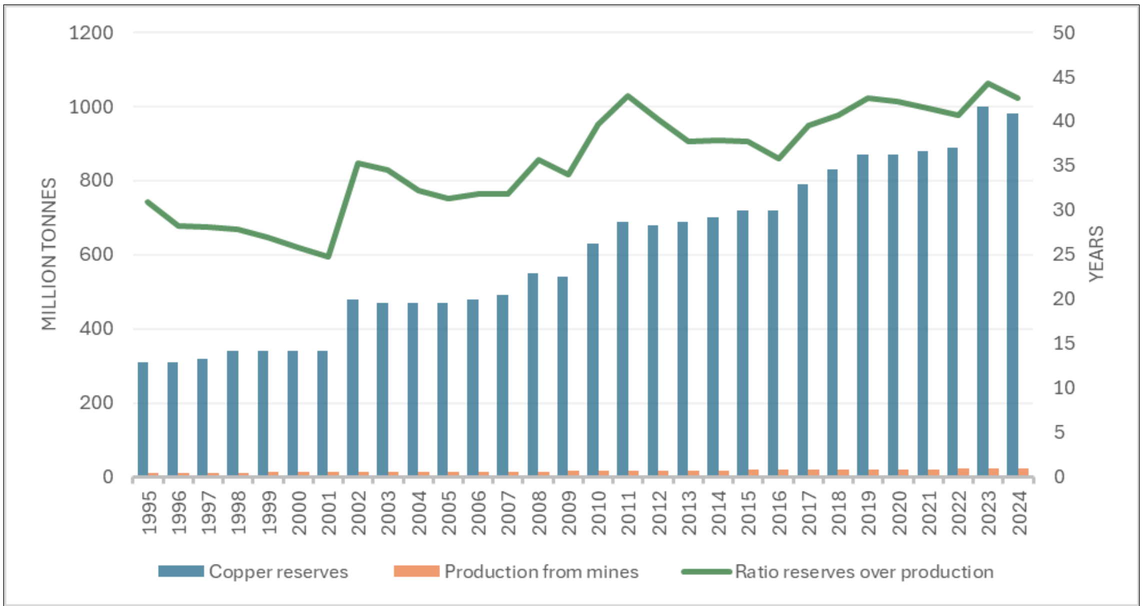
Reserves and resources

The distinction between reserves and resources is usually and rightly presented as economic: reserves are those parts of ore deposits that can be exploited using current technologies at current prices. Resources are "concentrations of naturally occurring mineral material of economic interest in or on the Earth's crust in such form, quality and quantity that economic extraction of a mineral commodity is currently or potentially feasible" (USGS, 2018). Hence neither of the two notions is purely geological. Resources are not reserves, the latter which need to be confirmed by someone who qualifies as a "competent person", i.e. a geoscientist with sufficient experience working on the relevant style of mineralization and who is a member of an accredited professional organization. This matters because reserve estimates directly affect a company's asset value, which in turn impacts its ability to raise money—whether by taking out loans or selling shares.

Government agencies closely monitor how these terms are applied, and the experts and companies responsible for signing off on ore reserves and related estimates can be held legally accountable.

It is important to recognise the dynamic nature of reserves, as illustrated by the following statistics: the USGS estimates that the world copper ore reserves at the end of 2023 were about 1 billion tonnes of recoverable copper metal (figure 7). This represents a tripling of the value of 325 Mt at the end of 1995, despite production increasing from 10.5 Mt in 1995 to 23 Mt in 2023.

Figure 7: Evolution of copper reserves and production since 1995



The green line represents the estimated "lifetime" of reserves, calculated by dividing known reserves by annual production.

Source: "Mineral Commodities Summary 2025", USGS, 2025.

Reserves depend on the metal price, increasing as the price increases, which allows lower-grade deposits to be mined, or slowly decreasing as the price drops. The price of a tonne of copper evolved around US$ 2,000 in the 1990s. It jumped to around US$ 6,000 in the late 2000s and currently oscillates between US$ 8,000 and 11,000 –quadrupling in current terms and roughly doubling in constant money, once dollar inflation is considered.

At the scale of an individual mine, reserves diminish as ore is mined out and increase as drilling and other exploration methods demonstrate that additional ore is available. Commonly, this involves the transformation of resources into reserves. Reserve estimates increase when technology improvements make mining and ore treatment more efficient. The same dynamic applies on a global scale, which explains why, despite constant and increasing production, global reserves of copper and most other metals have either remained constant or have even increased.

Estimates of copper resources are far larger. The USGS (2025) indicates that the identified resources contain 1.5 billion tonnes of unextracted copper and undiscovered resources contain an estimated 3.5 billion tonnes of copper. The resources estimated by the USGS (2025) are restricted to deposits within 1 km of the surface for porphyry deposits and within up to 2.5 km of the surface for sediment-hosted stratabound deposits, based on current practical limits to conventional mining techniques. As will be seen in section III, if technical improvements of both exploration and exploitation methods increased these limits, the resource estimates would be larger.

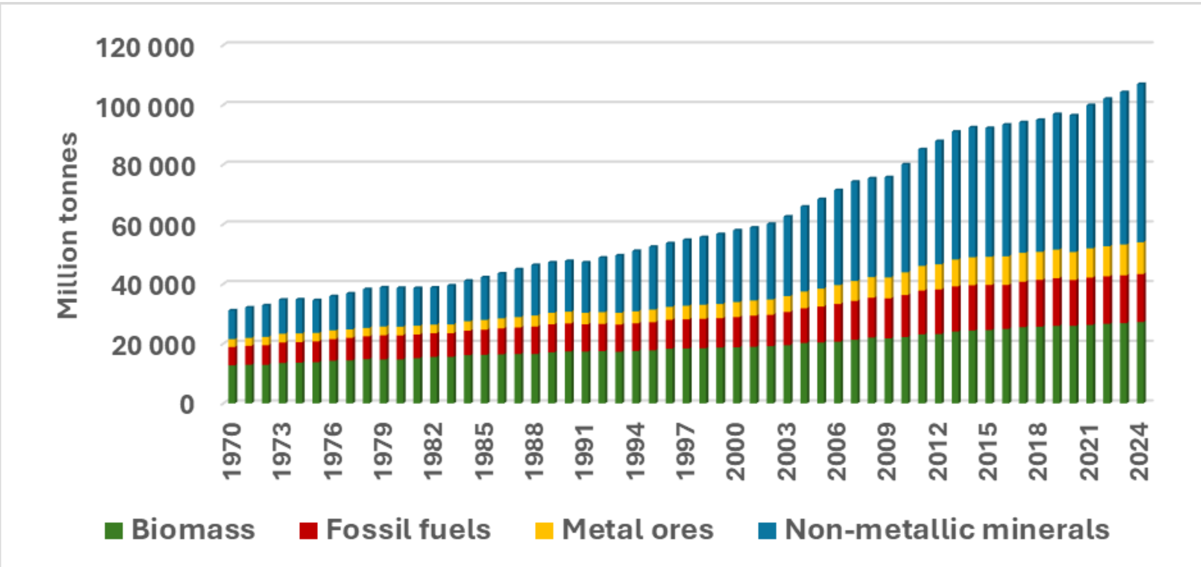
The environmental conditions of metal mining

This section first examines metal mining within the broader context of global resource extraction, then explores the evolution of its energy demand and associated GHG emissions, its water consumption and waste generation, and finally, its impact on biodiversity.

Metal mining and global extraction

Too often, the environmental impacts of all resource production are attributed to mining but metal extraction is only a subset of global resource extraction. According to the global material flows database of the United Nations Environment Programme (UNEP), almost 106 billion tonnes of materials were mined in 2024. As shown on figure 8, limestone for cement, gravel, etc. account for half this mass, biomass (forestry, agriculture) a quarter, and fossil fuels (almost entirely coal) 15%. Metal mining accounts for only 10% of the total.

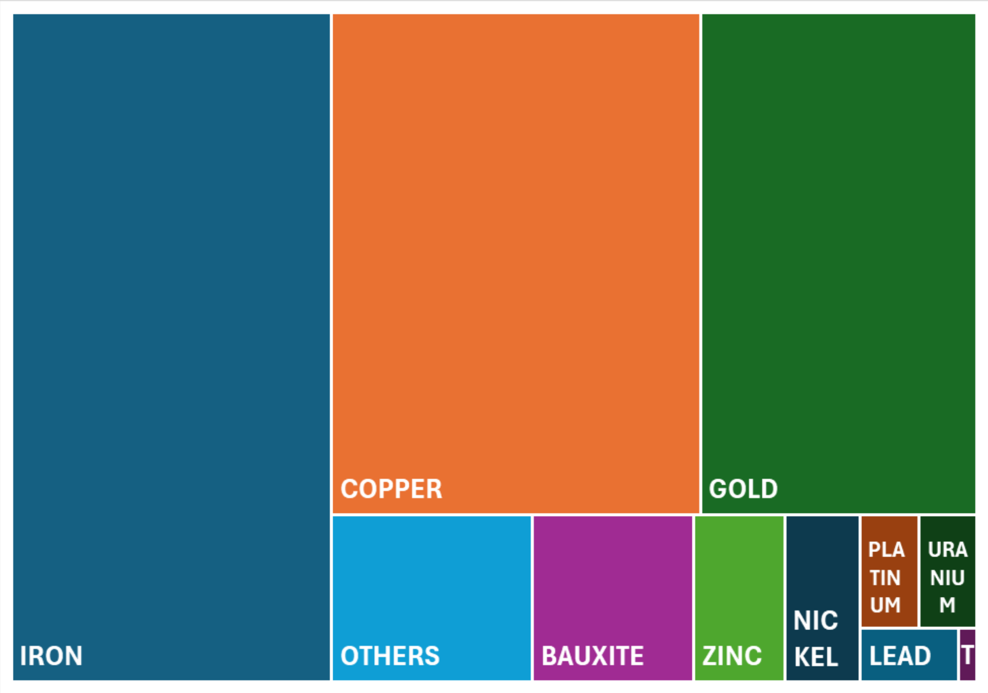
Figure 8: Global resource extraction from 1970 to 2024 (Mt)



Source: "Global material flows database", UNEP, 2025.

Of the 10.6 billion tonnes of ores that are mined, iron and gold represent over 50% (Figure 9). In 2021, copper contributed 29%, bauxite (4.2% for aluminum), zinc (2.3%), nickel (1.9%). Other metals contribute about 5%.

Figure 9: Relative tonnages of ores and concentrates per metal in 2021



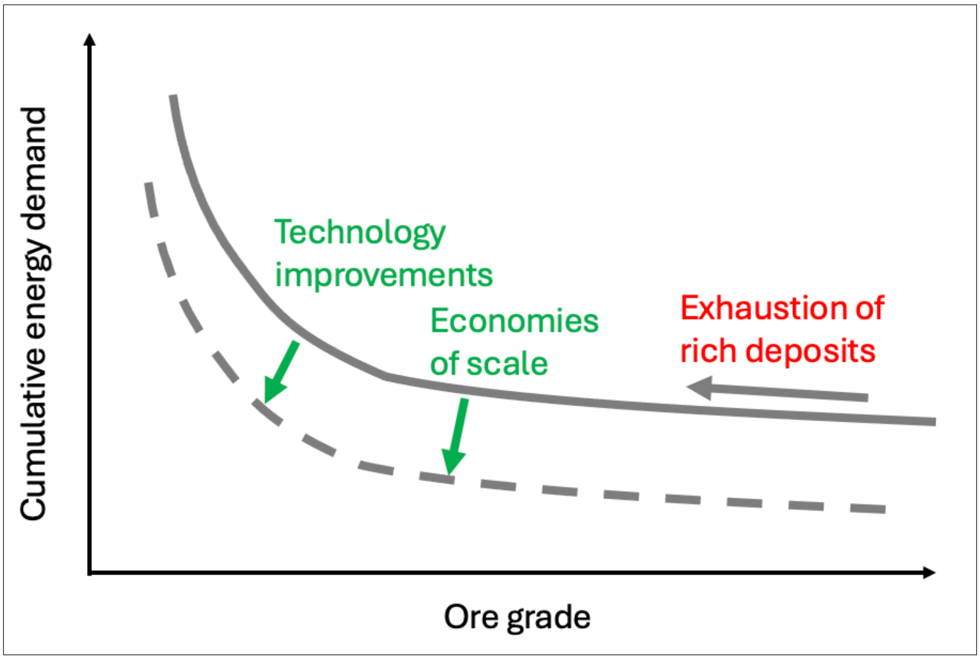
Source: "Material Profile for Metal ores", Wirtschaftsuniversität (WU) Vienna, 2023.

Energy and greenhouse gases

Over the past 20 years, the energy consumed during the production of metals and all minerals has almost doubled. Feix and Hache (2025) cite two main factors: the widespread use of less energy-efficient technologies in emerging countries like China for iron and steel production, and declining ore grades. A closer examination reveals that the first factor by far outweighs the second. Iron and steel production accounts for the bulk of energy consumption and GHG emissions, generating over 3.7 billion tonnes of CO_2-equivalent per year, compared to 97 Mt CO_2-equivalent from copper extraction and refining, even though the total tonnages of copper and iron ore mined annually are similar. Emissions from copper mining are only a small fraction (~5%) of the emissions associated with the mining and refining of iron and contribute only 1.5% of the total energy consumption of the minerals industry.

Nonetheless, the energy consumption of mining does increase as the ore grade declines – everything else being equal. Moreover, the reduction in ore grade often coincides with a reduction of the grain size of ore minerals, and consequently low-grade ores must be ground more finely (Michaux 2021). As the ore grade approaches zero, the required energy tends to infinity, but the costs of mining and processing low-grade ore will become prohibitive before this limit is reached. Still, technology improvements and economies of scale will likely outweigh the negative effect of declining ore grade, as illustrated in figure 10. Vidal et al (2022) show that the average efficiency of mining is about 1/3, thus leaving ample room for further improvement.

Figure 10: Schematic representation of the relationship between ore grade and cumulative energy demand and the influence of different factors



Source: Modified after N. Rötzer and M. Schmidt, 2020.

In 1930, when the average ore grade was 1.7%, the production of one tonne of pure copper (or "cathode copper") required about 70 gigajoules. This dropped to 53 GJ in 1970, despite ore grades declining to 1.3%, mostly due to the progressive domination of open-pit mines over underground ones, and improvements in mining technologies and electricity generation. The required energy then increased slightly to 69 GJ by 2010, mostly due to further reduction of average ore grades to 0.7%. Hence, in the past 80 years, technical improvements have kept the energy demand per tonne of copper nearly constant, despite a sharp reduction in ore grades from 1.7% to 0.7% (N. Rötzer and M. Schmidt, 2020).

Meanwhile, the associated contribution to GHG emissions have declined from 5.7 to 4.5 t CO_2-eq/t Cu in 2010, and less than 4 t today. Some of the best performances are reached in mines with low ore grades (0.25%), such as Boliden's Aitik mine in northern Sweden (Boliden, 2025). The move towards renewable energy procurement is fully engaged, with dedicated large-scale solar and wind power projects on all continents. Chile leads the way with a mining-dedicated 4,500 MW of solar and wind capacities, followed by Australia and hydropower-rich countries such as Canada or Sweden. At the same time, the electrification of large gasguzzling machines and haul trucks, which started around 2015 with pilot projects, is accelerating. Some mining companies attempt to save fuel by combining on-board diesel generators with trolley poles and catenaries, while others go for full battery-electric trucks or in-pit crushing and conveying. For example, the Australian mining company *Fortescue* recently ordered to *Liebherr* 360 autonomous battery-electric haul trucks, as well as 60 bulldozers and 55 excavators. Electrification of haul trucks, the biggest single source of CO_2 emissions from mining, is cost-effective where electricity can be procured at a relatively low price. Particularly if this energy comes from renewable sources, it has a negative cost per avoided tonne of CO_2 (Legge et al., 2021).

Global copper mining and refining are currently responsible for 97 Mt CO_2-eq per year. Of these, 70% were generated by mining, 23% from smelting and refining and the remaining 7% from upstream and downstream transport and in the end-of-life treatment of sold products (ICA, 2023). Doubling copper production would increase emissions by a comparable amount, reaching a total of ~195 Mt CO_2-eq if nothing else changed. But the future reduction in GHG emissions per tonne of Cu will most likely outweigh the possible increase due to the reduction in average ore grades to 0.53%. GHG emissions from copper mining and refining should, at worst, remain near constant until at least 2050, given the abundance of reserves with this average grade (see section III).

The copper paradox is that we need to mine and refine ever more of the metal in the short-to-medium term to enable technologies that will dramatically reduce emissions in other sectors. The temporary increase in emissions from copper production will be vastly outweighed by the emissions reductions it enables in other applications.

Waste and water

The reduction in average ore grade and the increase in open-pit mining over underground mining directly impact the volume of waste rocks and tailings produced by mining and concentration processes. These can be major sources of pollution of soil and water. About 23 million people, 6 million livestock and 66,000 km^2 of irrigated land are directly exposed to dangerous concentrations of toxic waste accumulating in river systems due to metal mining activity (Macklin et al. 2023). Artisanal and small-scale mining has a disproportionate environmental impact because it contributes only 15-20% of the production of metals such as gold or cobalt but degrades local environments, while being associated with highly polluting technologies and practices, such as uncontrolled smelting and refining, use of mercury and cyanide and improper waste disposal (de Haes and Lucas, 2024).

Mining is often presented as a large consumer of water. Copper mining requires between 50 and 100 liters of water per kilogram of copper, used in dust suppression, flotation, leaching and other applications. However, such figures need to be put in perspective with water demand from other activities, such as agriculture, textile production, or fossil-based electricity generation. For beef, a figure of 15,000 liters per kilo is often cited. However, the French Institute for Agronomic Research and the Environment (INRAE) explains that most of the water used in beef production is not extracted from the water cycle: 95% is "green water", i.e. rainwater that infiltrates the soil and is stored in the root zone, where it is used directly by plants. "Blue" water –surface water (rivers, lakes, reservoirs) and groundwater (aquifers) that can be extracted for irrigation, industrial use, and domestic consumption– accounts for only 3-4%. "Grey" water –wastewater from households and industries that has been used but is not heavily contaminated and can often be treated and reused for irrigation or other non-potable purposes– accounts for 1%. For beef, blue and grey water amounts to only 550 to 700 litres of water per kilo (INRAE, 2019). Another important concept is "useful water", which refers to the amount of water that is used and not returned to its original source during a process, making it unavailable for immediate reuse in the same watershed. Figures over 15,000 liters of water per kilogram of chocolate or coffee beans are similarly meaningless in the absence of local contexts. Perhaps more telling is the consumption of blue and grey water by the textile industry – 700 to 1,500 liters for a single 600g pair of jeans, over ten times the water consumption of copper.

Globally, when compared to other sectors, mining accounts for a relatively small proportion (~0.1%) of total water use (de Haes and Lucas, 2024). Still, water scarcity is a major challenge for copper production, especially in arid regions where many of the largest mines operate. The industry's high-water demand, combined with competition from agriculture and urban needs, makes water management a critical sustainability issue. As ore grades decline and mines deepen, water demands increase, intensifying conflicts with local communities and industries. Climate change further complicates the issue, altering water availability in key mining regions like the Andes, where supply could drop by 30% by the end of the century.

Chile, the world's largest copper producer, exemplifies this challenge. The Atacama Desert, one of the driest places on Earth, hosts highly productive mines but faces extreme water scarcity. Competition for the resource is fierce: in Chile, the agriculture sector consumes around 72% of available freshwater, and the mining sector around 4%. The mining sector's contribution to the country's 2022 GDP was 13.6% and mining exports reached 58% of the country's total exports. For comparison, agriculture and related sectors represented only 8.5 % of total GDP and 27% of total Chilean exports (Global Business Reports, 2022).

To address the challenge of water consumption, the industry is continuing to innovate in water management, exploring dry-stack processing and alternative fluids during mineral processing, and procuring additional sources of water. In northern Chile, 28 seawater desalination plants are operating or under construction, delivering currently 8,000 liters per second of water to multiple mines. This figure will grow to 25,000 liters by 2028.

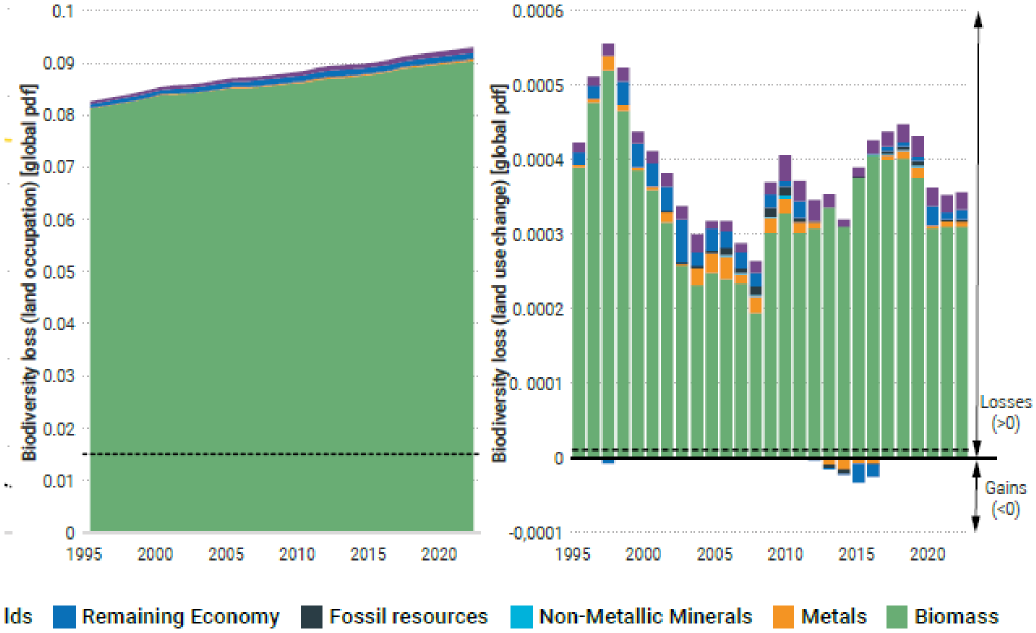
Water scarcity also affects energy use and local ecosystems, requiring an integrated approach. Sustainable solutions, technological advancements, and collaboration will be vital for balancing copper demand with environmental and social responsibility.

Impact on biodiversity

As with other environmental issues, local impacts of mining and refining operations can be considerable. However, they only represent a small minority of global impacts. Figure 11 shows land-related biodiversity loss split between material resource groups (including agriculture, mining and processing) and downstream use (household use and the remaining economy, according to UNEP's International Resources Panel.

A telling example of the perceived impact of mining on biodiversity is provided by the lateritic nickel mines in Indonesia. According to Jong (2024): "A massive nickel mining and processing project on the Indonesian island of Halmahera has cleared thousands of hectares of forest, forcefully displaced local people, and polluted the rivers and sea, devastating the lives of many Indigenous people in the process." The article reports the experience of local people who complain that the company that mines the Weda Bay deposit forced them off their land, degraded hunting in the region, and polluted local rivers and coastal waters. While many of these reports are no doubt true, their total impact must be put in perspective. Jong (2024) reports that 5,331 hectares of forest were cleared for the mining and processing plants, a figure that is readily verified using Google Earth images. This seems like a large area, a total of 5.3 km^2, but the mine is located on Halmahera Island, which has an area of 17,780 km^2. In other words, mining has affected only about 0.03% of the forest on the island. Another smaller mine in the south of the island contributes another small amount. This compares with the area used for agriculture (mainly coconuts, cloves and palm oil) which, at 1,060 km^2, covers about 6% of the island. Forests on the remaining 93% of the island are largely unaffected.

Figure 11 : Impacts of various human activities on biodiversity losses through land occupation (left) and land use change (right)



Source: Bruyninckx et al. "Global Resources Outlook 2024".

Runoff from the nickel mines has polluted local rivers and coastal waters. The main pollutant is waste lateritic soil, which contains only low concentrations of toxic heavy metals or sulfides that increase acidity. However, the suspended sediment limits the penetration of sunlight and impacts local fauna (fish and corals). But again, these impacts must be put in perspective. Weda Bay, where the deposit is located, is a broad open cove where pollution from the mining operations affects at most a few hundred kilometers of coastline. This represents a minute portion of the total coastline of Halmahera Island.

Most major copper mines are located in sparsely populated, commonly arid, regions where there is relatively little competition between mining and agriculture or biodiversity-sensitive regions. For example, the Atacama region in northern Chile hosts many major copper mines that contribute to the country's position as the world's dominant source of this metal. Chiquicamata, one of the world's largest mines, sprawls over an area of close to 400 km², while smaller mines such as MontoVerde, Las Bronces or Candelaria, cover 30-40 km². A rough estimate of the area occupied by all the mines in the region could amount to 800 km², to which could be added a similar amount for mine-related infrastructure. This amounts to less than 2% of the 75,176 km² of the Atacama region.

An area where copper mines co-habitat with agriculture is in Andalusia region in southern Spain. Figure 12 shows the operating Las Cruces mine to the right and the now-defunct Los Frailes mine to the left, surrounded by a much larger area covered by wheat fields and orchards.

Figure 12: Image of part of Andalusia southern Spain where mining and agriculture co-exist

Source: Google Earth.

Both are small mines, each covering less than 10 km², and under normal circumstances their impact on the local agriculture and environment is minimal. The two activities have operated together in the region since Roman times. This situation was disrupted in 1998 when a tailings dam at the Los Frailes mine burst, releasing an estimated 4-5 million cubic meters of acid tailings into the local river system, causing immense damage to the surrounding environment. The total cost of the clean-up is approaching $ 500 M. As a result of this disaster, and more catastrophic tailings dam failures in Brazil, or the largely uncontrolled dumping of tailings into rivers downstream from the Grasberg mine in Papua, stringent new measures are being installed at mines throughout the world. These include continuous monitoring of tailings dams using a variety of geophysical and remote sensing techniques and new safer methods to stabilize tailings, including dry stacking.

In numerous media reports and articles in scientific journals focusing on climate and environmental issues, the impact of mining is described in strident terms: “Indonesia’s abundant nickel reserves are crucial for a low-carbon world. But extracting them is ruining local people’s lives and causing rampant deforestation”. More nuanced reports are difficult to find. Lo et al. (2024) compared the positive and negative impacts of mining and concluded that diminished "environmental well-being" outweighed the improved economic and social benefits in many localities. Michel (2024) provides detailed information on the contribution of mining to the Indonesian economy (almost 10% of GDP and 30% of exports). The latter report also points out that a large part of the environmental impact of mining and processing comes from the use of coal; steps are being taken to replace this with renewable energy sources.

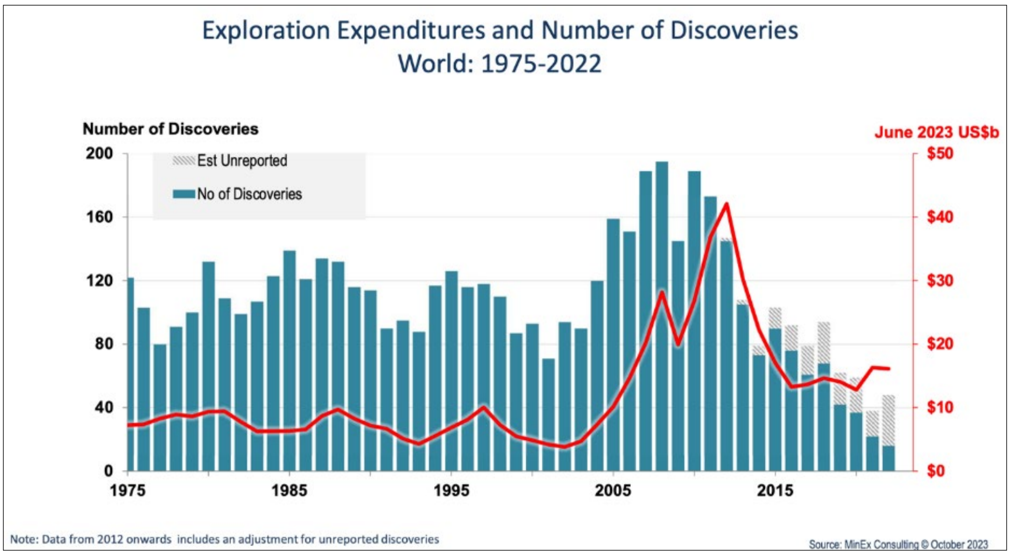
About a third of global tailing volumes are created from copper mining. A serious environmental issue is acid mine drainage: the exposure of sulfides to oxygen and water forms an acidic and toxic liquid, which eventually contaminates surface and underground waters.

Against this backdrop, systematically improving mining operations, reaching out and taking into account local communities, is and will remain paramount for the social license to operate and increasingly also for accessing funding and markets. Strict standards exist that need to be thoroughly implemented, such as the Initiative for responsible mining assurance.

The future of mining, and the power of technology

According to the estimates made in previous sections, the yearly demand for copper will double by 2050. An interesting way to express this demand is the claim that a major new deposit must be discovered every 1-3 years, depending on the magnitude of future demand (e.g. Cathles and Simon, 2024). This runs counter to recent data that show that despite greatly increased spending on mineral exploration, the number of new discoveries of deposits of all metals has declined (figure 13). Where, then, will we find these new sources of copper?

Figure 13: The evolution of global mineral exploration budgets and the number of new discoveries of metal deposits

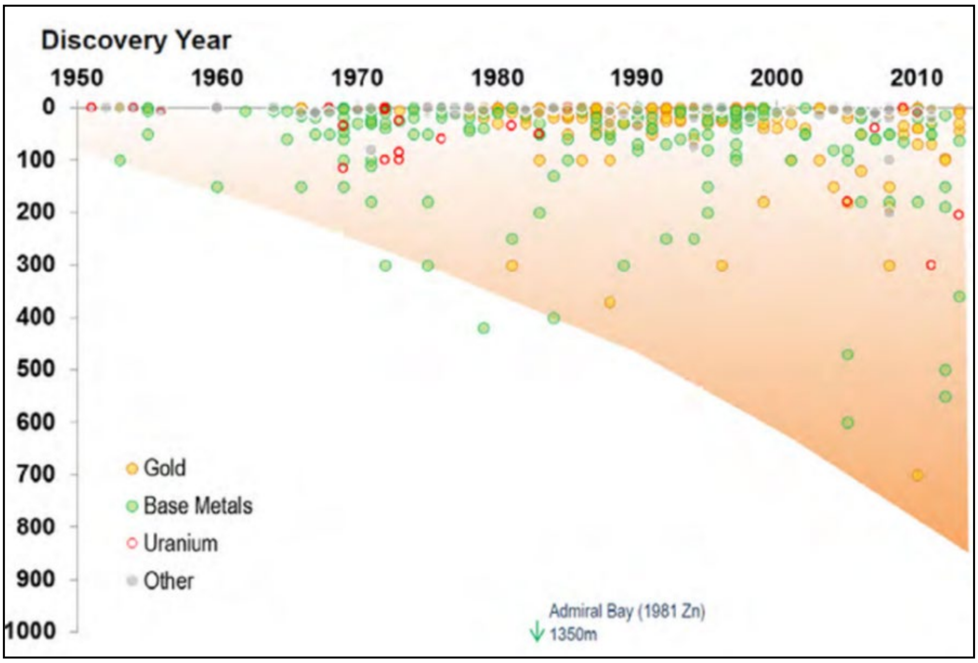


Source: MinEx Consulting, October 2023.

Digging deeper?

One possibility is that they will be sought deeper in the Earth's crust. Figure 13 shows that over the past 70 years, the depth of newly discovered ore deposits has progressively increased.

Figure 13: Evolution of the depth of newly discovered ore deposits



Source: Nickless et al., 2015.

The increasing depth of discovery is due mainly to two factors: 1) with increasing exploration in most parts of the world, the majority of easily discovered near-surface deposits have been found, and 2) new exploration technologies, mainly geophysical, are now capable of detecting deposits well below the surface.

Kesler and Wilkinson (2024) explored the idea that large amounts of copper and other metals remain to be discovered deep in the crust. They assumed a mining limit of 3.3 km in the near future and estimated a recoverable copper resource of about 89 billion tonnes. At double the current extraction rate, this supply could sustain global copper production for over 2,000 years. A key question, however, is whether such deep-seated deposits could ever be discovered. Most current exploration techniques depend on information obtained at the surface, followed by drilling. This applies to all geological and geochemical approaches, which have been instrumental in the discovery of most deposits in the past. Geophysical methods can penetrate deeper, but the most commonly used methods yield reliable information only to depths of a few hundred metres. Magneto-telluric, high-performance electromagnetic and seismic methods provide information to depths of several kilometers, but the resolution of these methods degrades rapidly with increasing depth. The cost of drilling prohibits its use except during exploration for deep extensions of known deposits, or where geophysical methods have revealed strong anomalies at depth.

Given the difficulty of locating deposits at or near the surface, it is likely that only a small fraction of deeper deposits will ever be discovered. In addition, once discovered, the possibility that they are mined is not assured. With increasing depth, the cost of mining increases dramatically, due to a multitude of factors –increasing energy needed to transport ore to the surface, increasing temperatures that must be controlled by expensive ventilation, increasing danger of mine structural failure, and so on. Because of this, for a deep deposit to be mined, it must be richer or bigger than a similar deposit near the surface.

A survey of operating deep mines shows that the great majority are extensions of deposits located at the surface –eight of the ten deepest are gold mines near Johannesburg in South Africa, where mining has progressed from near the surface over a century ago to present depths near 3 km. There are very few examples of isolated, deep deposits that do not extend near the surface. Olympic Dam, a very large and rich multi-element deposit in Australia, is an exception because it is covered by about 300 m of sedimentary strata, and while the exploration campaign was guided by sound geological principles, the discovery of the deposit was largely accidental (Haynes, 2006).

Still, faced with the prospect of the forthcoming gap between copper supply and demand, mining companies are looking to extend and expand current mines, including by turning some of them from open-pit to underground exploitation. For example, the Kidd Creek mine in Canada started operations as an open pit mine in 1966 then transitioned to an underground mine in 1972. It is currently the world's deepest base-metal mine with operations at almost 3,000 meters depth. Additional ore is known to exist at deeper levels, but a plan to extend the mine was shelved because operating more than three kilometers deep was found to be challenging from a technical and economic point of view. More recently, Codelco is turning the world's largest open-pit mine, Chuquicamata, into an underground operation to maintain production rates and extend the life of the century-old mine by over 40 more years. The company submitted its environmental assessment in February 2024 and anticipates the mine to reach capacity by 2030. It may use the emerging mobile tunnel borer technology for mechanized horizontal development.

While it is unlikely that 89 billion tonnes of copper predicted by Kesler and Wilkinson (2024) will ever be mined, improved exploration and exploitation methods may allow mines to descend somewhat deeper than today. As was the case in the past, both reserves and resources will probably continue to expand (figure 7) and deliver enough copper for the transition towards renewable energy. The popular view that the earth's resources are finite is obviously correct, but exhaustion is not in sight. There is in general no shortage of energy for the mines (and investments in hydro generation are for example planned in DRC to power mining operation, water availability in reservoirs being a challenge though in the context of climate change), and their environmental footprint and environmental impact, including GHG emissions, can be controlled, in part using the novel methods discussed below.

Finally, while new deposits of metals like copper, zinc, gold, and cobalt may still be discovered at depth, the approach has limited applicability for deposits formed by weathering near the Earth's surface. The latter category includes almost all aluminium deposits and a significant portion of nickel, lithium, zirconium/titanium, and rare earth element deposits. Unless deposits of these types have been covered by younger volcanic or sedimentary rocks, or buried by tectonic processes, they will not be found at depth.

Technology improvements

There is a breadth of technical improvements that could reduce costs, improve efficiency and reduce environmental impacts in both exploration and exploitation of copper mines. Many have already been introduced in a few mines, and others are options for the future.

- **Electrification and renewables**. Electrification of haulage is well underway. It will reduce energy consumption by eliminating Carnot losses. Coupled with the deployment of renewable energy assets, now shouldered by battery storage, it will reduce even more GHG emissions (Li et al., 2024).
- **Artificial intelligence and machine learning** are revolutionizing copper mining, from enhancing exploration methods to optimizing production processes. For exploration, algorithms can integrate data from multiple sources to create 3-D models of potential copper deposits. They are also set to optimize various aspects of the mining and processing chain, from self-driving fleets of haul trucks to analyzing satellite imagery, to the detection of early signs of vegetation stress or changes in water bodies, allowing rapid intervention to prevent environmental damage (Kwan, 2024).
- **Primary sulfide leaching** of waste rock could increase copper production by 5 Mt by 2035, thus turning an environmental liability into an economic opportunity (Turner and Reinaud, 2024).
- **In situ leaching**. This mineral extraction method leaves the source rock intact. A solution is injected underground to dissolve the target minerals, and the resulting mineral-rich solution is then pumped to the surface for metal extraction. The approach minimizes surface disruption and avoids the production of tailings or waste rock. For the technique to be effective, the orebody must be sufficiently permeable to allow fluid movement and must be in a geological context that prevents groundwater contamination. The process is currently used to extract uranium at sites in Kazakhstan, the USA and Australia. It has

had only limited application for the mining of copper and other metals, however, in part because most orebodies have low permeability that prevents efficient circulation of fluids. Recent laboratory-scale experiments suggest copper can be extracted from porphyry ores by means of electrokinetic in-situ leaching. This technique involves the application of a low-voltage direct or alternating electric field across a section of ore deposits, which induces the migration of a leaching agent that mobilizes the ore metals (Martens et al., 2021).

- **Secondary mining.** Tailings offer opportunities for secondary mining, the practice of extracting valuable metals from previously mined materials or waste. Global tailings are said to host 100 million tonnes of copper. In Chile, the company Amerigo Resources has been working on this possibility since 2003 and recently increased its production significantly. Ore sorting with sensors such as laser radiation, finer grinding technologies or improved solvent extraction and electrowinning methods can make profitable metal extraction that was not profitable at the time of primary mining.
- **Underground mining**. An evolution to underground mining, primarily driven by innovative block caving methods, could reduce the volume of tailings and waste rocks, as well as air pollution and total footprint.
- **Green explosives.** In Chile, the company Enaex delivers to the copper miner Codelco explosives made with blue hydrogen, thereby reducing associated GHG emissions by about 40%. In Peru, it uses an old electrolyser in Cusco to produce green hydrogen and ammonia and delivers "green explosives" to Peruvian mining companies. In Sweden, the company Hypex Bio produces nitrate-free, hydrogen peroxide-based explosive and claims it reduces associated GHG emissions by over 74%.
- **Pulse power.** Communition (crushing and grinding) currently absorbs about 37% of the energy used during mining (Purhamadani and Bagherpour, 2024), growing over time as ore grade and the copper particle size both decrease. To increase the efficiency of the process, novel techniques are being developed. One approach is to use high-performance explosives to break the ore. Pulse power generators, another technique that promises to reduce electricity demand by up to 80%, store electrical energy, compress it in time and space, and deliver it as a strong, fast and short high-power pulse. Low-power electric energy is thus turned into very short pulses with enormous power. Instead of placing a compressive force on the outside of a rock until it breaks, pulsed power creates electric arcs that pass through the rock, causing it to burst and separate individual mineral grains.

Conclusion

There is no doubt that mining will continue well into the future. It is needed to satisfy the booming demand for a wide range of raw materials, not only the much-vaunted critical metals, but also more common metals like iron and copper, which will be needed to build the infrastructure of the energy transition. Recycling will play an increasing role but only in a few decades' time, when sufficient stock has accumulated and systems for collecting what we normally throw away have become efficient.

Earth's copper resources are indeed finite, but the amount that is accessible appears to be more than sufficient to meet demand for decades, and possibly centuries, to come. Estimates of copper reserves are sufficient for only a few decades of production, but it must be recognized that mining companies have no incentive to convert known resources into reserves before they are required. As in the past, continued exploration will continue to find sources of copper sufficient to meet the demand.

As a result, the risks to the energy transition are not rooted in the exhaustion of potential copper supplies but rather in potential delays in exploration and exploitation. Opening a new mine is a complex and time-consuming process that often faces significant opposition. Most of the future copper supply will likely come from extending the life of existing mines, through horizontal or vertical expansions or improvements in mining and processing methods.

At the same time, technological advancements are expected to reduce the specific energy consumption of copper mining and are likely to lower its overall GHG emissions despite a projected doubling of output by 2050. While the success of the energy transition is far from guaranteed and faces considerable resistance—notably from the White House—, copper mining will not be the cause of its potential failure.

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